

Rapidity particle spectra in sudden hadronization of QGP

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We show that the remaining internal longitudinal flow of colliding quarks in nuclei offers a natural explanation for the diversity of rapidity spectral shapes observed in Pb–Pb 158A GeV nuclear collisions. Thus QGP sudden hadronization reaction picture is a suitable approach to explain the rapidity spectra of hadrons produced.

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If a quark-gluon plasma deconfined state super cools and decomposes in a sudden fashion into free streaming hadrons [1], we should be able to see in the hadron spectra certain features of quark statistical distributions. Such a QGP fingerprint on m_\perp -spectra of strange baryons and antibaryons which are seen to be identical is one of key indicators for the sudden hadronization picture [2].

A question which has remained open is how sudden hadronization model can be reconciled with the diverse shapes of rapidity spectra of observed hadrons. Great differences are known to be present: while hadrons made of quarks brought into the collision, such as, e.g., protons, show a pronounced double hump structure, progressively more peaked distributions are seen for particles which are more and more composed of newly made quarks [3–5].

We present a schematic description of this phenomenon based on the assumption that the quark momentum distribution in QGP is imprinted on hadrons produced, and not erased in a post hadronization period. The model we explore is a direct continuation of the study of m_\perp shape and abundance of hadrons produced [6].

We note that many light quarks are brought into the collision fireball by colliding nuclei — in 158A GeV Pb–Pb central interactions there are 1000+ such valance quark participants and there is a similar total number of hadrons produced. In general the two incoming quark fluids can retain memory of the early stage in the collision: in the center of momentum frame two quark fluids collide with initial rapidities $y_i = \pm 2.92$. In order to reproduce the proton data, we assume in what follows, that the *average* remaining longitudinal quark flow is $y_f = \pm 1$. This average includes quarks from $q\bar{q}$ pairs produced, which are mostly found at central rapidity. We further assume that the average flow of \bar{s}, s, \bar{q} quarks is zero.

If quarks were not confined, their emission spectrum would be computed in a thermal emission model with flow. We proceed to establish this spectrum. Each emitting volume element is assumed to be in motion, with a

four-vector u^μ , and in the local frame at rest the temperature in the volume element is T , and the local quark distribution is of Boltzmann type. In order to count the states, we apply Touschek invariant phase space measure for the level density [7,8]:

$$\frac{V_0 d^3 p}{2\pi^3} e^{-E/T} \rightarrow \frac{V_\mu p^\mu}{(2\pi)^3} d^4 p 2\delta_0(p^2 - m^2) e^{-p_\mu u^\mu/T}. \quad (1)$$

Here, $V_\mu = V_0 u_\mu$ is the flowing volume element as observed in the laboratory frame. V_0 is the comoving volume element in the local rest frame. δ_0 is the Dirac-delta function for the positive roots only. This is an invariant function for all proper Lorentz transformations. Using the rapidity and transverse momentum p_\perp (or mass $m_\perp = \sqrt{m^2 + p_\perp^2}$) variables of a particle in a cylindrical symmetric decomposition with respect to the collision axis

$$p^\mu = (m_\perp \cosh y, p_\perp \cos \phi_p, p_\perp \sin \phi_p, m_\perp \sinh y), \quad (2)$$

we recover the well known invariant measure in Eq. (1):

$$\begin{aligned} 2\delta_0(p^2 - m^2) d^4 p &= \frac{d^3 p}{E} = m_\perp dm_\perp dy d\phi_p \\ &= p_\perp dp_\perp dy d\phi_p. \end{aligned} \quad (3)$$

The four-velocity u^μ allowing for both transverse and longitudinal flows is:

$$\begin{aligned} u^\mu &= (u_0, u_x, u_y, u_z), \quad u^2 = 1; \\ u_0 &= \cosh y_\perp \cosh y_\parallel; \quad u_x = \sinh y_\perp \cos \phi_u; \\ u_y &= \sinh y_\perp \sin \phi_u; \quad u_z = \cosh y_\perp \sinh y_\parallel. \end{aligned} \quad (4)$$

We recall the usual relations:

$$\frac{m_\perp}{m} = \gamma_\perp = \cosh y_\perp, \quad \frac{p_\perp}{m} = v_\perp \gamma_\perp = \sinh y_\perp,$$

which illustrate the structural identity of Eq. (2) with Eq. (4).

It is straightforward now to obtain the quantity required to construct spectra Eq.(1),

$$u_\mu p^\mu = \gamma_\perp [m_\perp \cosh(y - y_\parallel) - p_\perp v_\perp \cos \phi], \quad (5)$$

where $\phi = \phi_p - \phi_u$. For a suitable choice of coordinate system in which the x -axis is pointing in the direction of transverse flow vector, $\phi_u = 0$, and we can use the particle emission angle as the azimuthal angle of integration for radiation emitted from the volume element: $\phi = \phi_p$. This has the advantage that we can easily restrict the counting of particles to those emitted *outwards* including $0 < \phi_p \leq \pi/2$ instead of the full range $0 < \phi_p \leq \pi$.

In Eq.(5), the emitted particle variables are as usual y, m_\perp and the flow vector variables used are y_\parallel and v_\perp with $\gamma_\perp = 1/\sqrt{1 - v_\perp^2}$. The invariant spectrum written explicitly is:

$$\frac{d^2 N}{m_\perp dm_\perp dy} = \int \frac{d\phi \gamma_\perp}{(2\pi)^3} [m_\perp \cosh(y - y_\parallel) - p_\perp v_\perp \cos \phi] \times e^{-\gamma_\perp [m_\perp \cosh(y - y_\parallel) - p_\perp v_\perp \cos \phi]/T}. \quad (6)$$

There are some differences in detail between this traditional expression [7,8] and recent proposals based on consideration of the freeze-out surface geometric properties [9]. Certain features we find are the same in both approaches: the rapidity y distribution is not appreciably influenced by transverse dynamics (i.e., transverse velocity and temperature), which effectively separates. The m_\perp spectra are only dependent on T, v_\perp , but practically not on the longitudinal flow y_\parallel . We note that Eq.(6) retains absolute number of particles independent of the flow parameters, if integral over ϕ includes the full range $0 \leq \phi \leq \pi$.

The rapidity spectra of massless quanta in the deconfined phase are shown in figure 1. We see how the thermal spectrum ($m = 0, T = 145$ MeV, $v_\perp = 0.52$) gradually ‘flows’ apart as y_\parallel is increased from $y_\parallel = 0$ (dotted) to $y_\parallel = 1.5$ (solid) in step of 0.5. Included in the double numerical integral (over ϕ and m_\perp) are particles emitted outwards with reference to the direction of the flow vector of the volume element. Model studies of kinetic dynamics show that inside the QGP matter we find a mix of fluids, the incoming quarks are still retaining some of the original flow while all newly made quark pairs have no memory of the initial condition of colliding matter. In particular, strange quark pairs made in the plasma do not flow.

Final state hadrons are born from deconfined quarks with such spectra. In the previously studied case of m_\perp spectra [2] it was found that the transverse flow parameters of the hadronizing quark matter were in agreement with results of chemical particle production parameters. Thus the shape of m_\perp spectra of hyperons, antihyperons and kaons was as if these particles were directly made of hadronizing QGP quanta. Addressing here the rapidity spectra we will take this point of view but proceed

more carefully. As hyperon are formed at the fireball breakup, any remaining longitudinal flow present among fireball constituents will be imposed on the product particle, thus Λ -spectra containing potentially two original valence quarks are stretched in y , which $\bar{\Lambda}$ - y -spectra are not, as they are made from newly formed particles. One would thus expect that anti-hyperons comprising only newly made quarks will appear without flow, while Λ -spectra will show flow, if such was still present.

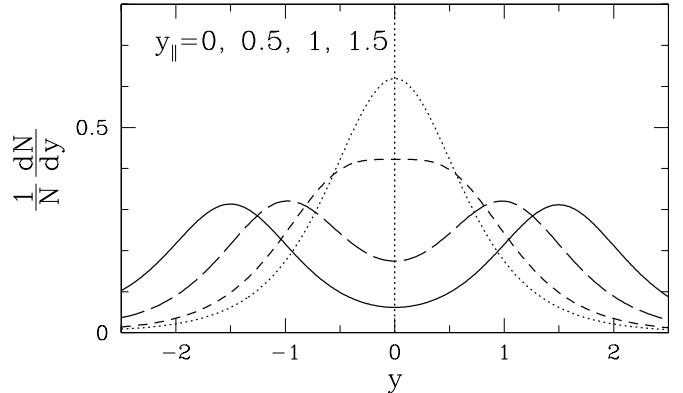


FIG. 1. Rapidity spectra with flow of massless QGP quanta: dotted: no flow $y_\parallel = 0$, dashed, $y_\parallel = 0.5$, longdashed $y_\parallel = 1$, solid, $y_\parallel = 1.5$.

We thus implement a particle-staged turn-on of longitudinal flow at SPS where in central Pb–Pb collisions the incoming valance quark number and total number of hadrons produced is about the same. For protons we assume that effectively all quarks are remembering some of the original flow. For Λ with one strange quark we take a mix of 2/3 weight in the spectrum with flow and 1/3 without. For particles like $K^+(u\bar{s})$ we take a 50-50% mix and for all newly made particles like $\bar{\Lambda}, \Phi$ we assume that only no flow components contribute.

To describe proton rapidity spectra we assume after inspection of [3] that the longitudinal flow is $y_\parallel \simeq \pm 1$, and choose this value without a further attempt to fit the spectra. With $m_q = 0, T = 145$ MeV and $v_\perp = 0.52c$ (both parameters could be chosen very differently without altering the result, these were taken in view of results of [2]), we obtain the proton rapidity spectrum we present in figure 2, bottom panel. We note that we have to average over positive and negative flows $y_\parallel = \pm 1$, since the collision in the CM frame involves both.

The strange quark content of the Λ contributes with relative strength 33% in the central region, which results in a flat distribution — see the second panel from the bottom in figure 2. Next we take a 50-50% mix which gives us the result shown in the third panel from the bottom, corresponding to the $K^+(u\bar{s})$ rapidity distribution and when resonance decays are considered, also pion distribution. Finally, in the top panel we show prototype of the rapidity distribution arising for all completely newly

made particles such as $\bar{\Lambda}, \Phi$. Though far from perfect, we see in this schematic study practically exactly the behavior observed.

The same schematic rapidity behavior is seen in S-S collisions at 200A GeV for the particles here considered. A direct comparison of the charged particle distributions between Pb-Pb and S-S collision systems seen in Ref. [10] suggests that y_{\parallel} is about 0.4 units of rapidity larger in the lighter collision system. Though seemingly a small change, this opens by 50% the gap between the fluids as we saw in figure 1 and a much more pronounced central rapidity reduction in certain particle abundances ensues.

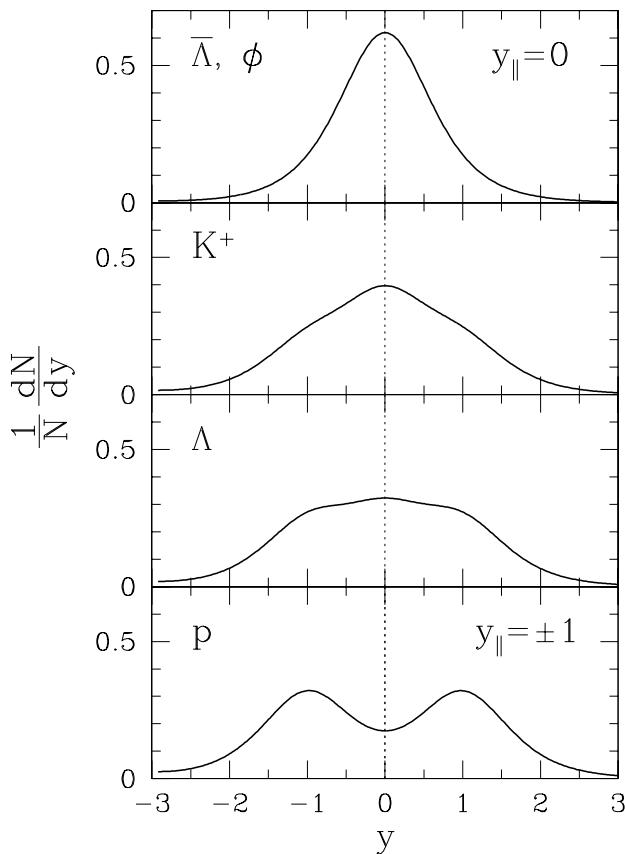


FIG. 2. Rapidity particle spectra: schematic representation within a thermal model with flow, parameters chosen for $\sqrt{s_{NN}} = 17.2$ GeV. See text for details.

Our schematic method can help understand the particle rapidity distributions at RHIC. The PHOBOS collaboration has presented a nearly flat distribution of charged hadrons with small peaks near to pseudo rapidity $\eta = 1.5$ at the edge [11,12]. Trying our model we finds that rather than to have a 3-fluid quark source, we need now a continuous distribution of sources residing in the range of rapidity $-1.6 \leq y \leq 1.6$. In other words if the hadron rapidity distribution is as before offering an image of the quark flow, we have a flow plateau as expected in the hydrodynamical scaling solution proposed by Bjørken [13].

In summary of this brief contribution, we have shown, within a schematic dynamic model, that quark flow in QGP can explain the diversity of particle rapidity spectra observed at $\sqrt{s_{NN}} = 17.2$ GeV, where clearly we do not see yet a high energy scaling behavior. What we have shown is that a three component fluid, two made of quarks still flowing against each other, and a third one made of newly made components (antiquarks, strange quarks), is capable to imprint on the rapidity spectra just the right systematic behavior. This transfer of quark dynamics to hadron dynamics is similar to what was found in the study of the m_{\perp} spectra. For hadrons to emerge with momentum spectra of quarks we need a hadronization with sudden breakup of the (super cooled) QGP plasma phase into free-streaming hadrons. Thus this study shows that such a picture is capable to explain rapidity spectra.

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